Layered Quantum Hall Insulators with Ultracold Atoms

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Three-dimensional layered fermion systems, where tunneling is suppressed along a direction, can be found in many areas of condensed matter physics ranging from graphite to high-temperature superconductors. In the limit when inter-layer tunneling is zero one can think about the layer index as a conserved quantity related to a global gauge symmetry generated by the discrete momentum along the direction perpendicular to the layers. By adding coordinate dependence to the symmetry group one arrives to a system with reduced dimension but in the presence of a gauge field with the Heisenberg-Weyl group as the gauge group. The Heisenberg-Weyl group is generated by the momentum $\hat{p}_z$, coordinate $\hat{z}$, and the identity 1, with the commutation relation $[\hat{z}, \hat{p}_z] = i 1$.

We investigate the integer quantum-Hall effect [1] with ultracold fermions in a 3-dimensional layered optical lattice described by the above dimensional reduction, i.e., by a 2-dimensional tight-binding model subjected to an artificial Heisenberg-Weyl gauge-field. The gauge-field coordinate is mapped to the third coordinate direction. By varying the strength ($\lambda$) of a staggered potential, changing sign from layer-to-layer, we see that nontrivial combinations of edge states (and therefore the transverse conductivities) can be engineered in some analogy to the quantum spin Hall effect [2]. As an example we calculate the zero temperature phase diagram of the system as a function of the Fermi energy $E_F$, and the strength of the staggered potential $\lambda$ (Fig. 1.) for a flux of $\pi/2$ per plaquette [3]. We relate the different phases to the possible edge state configurations (Fig. 2.).

![Fig 1: The phase diagram of the system. The different regions show different transport properties. The hatched regions represent metallic phases. The insulating regions have (or miss) edge states, according to the illustration in Fig. 2, and therefore can have different transverse conductivities $\sigma_\perp$.](image1)

![Fig 2: The edge state configurations of the different phases. (a) all of the layers are metallic, (b) all of the planes are trivial insulators without edge states, (c) all of the layers are quantum Hall insulators, but with alternating edge states from layer to layer, (d) all of the layers are quantum Hall insulators with accumulating edge states, (e) half of the planes are trivial and half of them are quantum Hall insulators, (f) half of the layers are metallic, the other half is in a quantum Hall state.](image2)

References

